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学位論文題目　Compressive Sensing Based Low-Complexity and High-Resolution Radar Signal Processing Algorithms
（圧縮センシングに基づく低演算量かつ高解像度のレーダー信号処理アルゴリズム）

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論 文 内 容 要 旨

Radar, an object detection system utilizing radio waves to determine the range, angle, or velocity of objects, has been applied in many fields, such as ground penetrating radar, ballistic missile defense, air-traffic control, law-enforcement, highway safety and automatic driving. The demand for modern radar systems with high resolution but low hardware and/or software costs has been increasing rapidly. Therefore, the topic of developing new radar signal processing algorithms to accomplish higher resolution has attracted considerable attention.

For range and velocity detection based on time sampling, a wide bandwidth radar signal is usually used to achieve high resolution, which leads to the requirement of a high sampling rate. Thus, the modern radar system requires a high-rate analog-to-digital converter (ADC) and accordingly a large memory capacity for the large amounts of sampled data. For angle detection based on spatial sampling, a sufficiently large number of snapshots are required for accurate estimation. These huge data produced in modern radar systems cause various difficulties in data processing. However, in practical applications, only few targets are concerned in a wide interested area, such as the case of searching some airplanes in a wide region of the sky, and thus the final outputs are often sparse. Hence, it is of great interest to detect the sparse targets more effectively and efficiently by establishing new methods to reduce and process the large amounts of sampled data.

Recently, it has been clarified that the compressive sensing (CS) theory can be used to reduce the number of sampled data for time and spatial samplings. Under the assumption that the targets are sparse, a class of novel methods based on CS have been proposed for digital radar signal processing to achieve a high resolution. However,

due to the causes stated below, these existing CS-based methods suffer from a high computational complexity for reconstructing signals and a low accuracy for non-Gaussian impulsive noise environment.

In view of this background, the purpose of this research is to develop a class of new CS-based methods having higher resolution, less computational complexity and stronger robustness against non-Gaussian impulsive noise than the existing CS-based methods. Specifically, both of the cases for time sampling and spatial sampling will be intensively investigated, and the main results and contributions are concentrated on the following aspects:

- For the time sampling case, the range and velocity joint detection problem is in fact a two-dimensional (2D) problem characterized by a matrix representation, while the existing CS-based methods treated this problem by first vectorizing the 2D matrix representation into a 1D vector representation and utilizing the well-known CS algorithms which is originally developed for 1D signal reconstruction. It is the dimension transformation (vectorization) operation that results in a huge measurement matrix for the resultant CS problem and thus causes a high complexity. To overcome this difficulty, 2D CS algorithms are first proposed that can directly solve a 2D signal reconstruction problem, and then 2D-CS-based methods for the range and velocity joint detection problem will be established so that the dimension transformation operation is no longer required and the computational complexity can be reduced largely.
- Moreover, since the existing CS-based methods for time sampling have been developed based on the assumption of Gaussian noise environment, the existing methods usually suffer a performance deterioration in a non-Gaussian impulsive noise environment. Therefore, robust-2D-CS-based methods are proposed by introducing new robust cost functions in the 2D CS algorithms so that the performance of CS-based methods for non-Gaussian impulsive noise environment can be significantly improved.
- For the spatial sampling case, the existing CS-based methods achieve the high accuracy of direction-of-arrival (DOA) estimation by gridding densely and searching the entire range of interest, which results in a huge measurement matrix. In addition, the inversion operation for this measurement matrix is required in each iteration of the algorithms. These two problems lead to the high complexity of the existing CS-based methods for DOA estimation. In order to avoid the first problem caused by the dense gridding, a two-step method is proposed: first, the range of interest is divided into a relatively low-resolution grid and the conventional beam former is used quickly identify the candidate or potential areas where true targets may exist; then the candidate areas obtained in the first step are divided into a denser sampling grid and the $L_{2,1}$-norm minimization algorithm is utilized to locate the targets with a high-resolution. For the second problem of inversion operation, a new adaptive algorithm is proposed without involving any matrix inversion operation. Simulation results show that the proposed methods have much lower complexity and higher accuracy than the existing CS-based methods.

This thesis consists of 8 chapters and is organized as follows.

1. **Introduction:** This chapter briefly introduces the background and motivations of this research as well as an given overview of the main results obtained in this thesis.
2. **Signal model for delay Doppler joint estimation with sub-Nyquist rate:** In this chapter, the principle of the delay Doppler radar system and the mathematical models for delay Doppler joint estimation in sub-Nyquist radar systems are first presented. Then, the existing methods that closely relate to the technical development of the thesis are reviewed.
3. **2D-CS based methods for delay Doppler joint estimation:** To reduce the complexity caused by the

dimension transformation, four 2D-CS-based methods, i.e., 2D-ZAP, 2D-IHT, 2D-ISTA, and 2D-FISTA, which use a matrix norm instead of the vector norm to avoid the dimension transformation, are established directly in this chapter. Simulations are presented to validate the performances of our proposed methods.

4. **Robust 2D-CS methods for delay Doppler joint estimation:** In this chapter, it is first shown that the performance of the traditional CS-based methods usually deteriorates in a non-Gaussian impulsive noise environment. Then, several kinds of robust 2D-CS-based methods are proposed. The cost functions of these robust methods are constructed using the L_1-norm, L_p-norm and Lorentzian norm, and thus have a better robustness to the non-Gaussian impulsive noise. As a result, the accuracy can be significantly improved by the proposed methods for the non-Gaussian impulsive noise environment. Simulations are also presented to validate the performances of our proposed methods.
5. **Direction-of-arrival (DOA) model for the multiple-input-multiple-output (MIMO) radar system**: This chapter introduces first the principle of the MIMO radar system and the mathematical models for the DOA estimation problem, which is a key problem in the MIMO radar system. Then the existing methods closely relating to the technical development of this thesis are reviewed.
6. **Dimension-reduced DOA estimation based on L2,1-norm penalty**: In this chapter, in order to overcome the difficulty of high computational complexity caused by the dense sampling grid, we develop a two-step method. In the first stage, the range of interest is divided into a relatively low-resolution grid, and the conventional beam former is used to quickly identify the candidate or potential areas where true sources may exist. In the second stage, the candidate areas obtained in the first stage are divided into a denser sampling grid, and the CS-based method is utilized to locate the targets with a high-resolution.
7. **Adaptive filtering algorithms for DOA estimation with small snapshots**: In this chapter, a novel adaptive filtering algorithm for DOA estimation is proposed. It incorporates a mixed norm ($L_{2,0}$-norm) to exploit the advantage of multiple snapshots to improve the accuracy. Moreover, it uses a row in the manifold matrix in each iteration to avoid matrix inversion operation. Therefore, the low complexity is achieved with a high accuracy.
8. **Conclusions and further works:** In this chapter, the main results and contributions obtained in this thesis for low-complexity and high-resolution radar signal processing algorithms based on CS theory are briefly summarized. In addition, some possible future topics are also discussed.

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論文審査結果要旨

圧縮センシング(CS)に基づく MIMO(マイモ)レーダー信号処理技術はナイキストレートより低いサンプリングレートを用いても高精度の目標探知ができるメリットで注目されている．しかし，既知アルゴリズムは演算量が多く，非ガウスノイズ環境で精度の低減が激しいなどの問題点を持っている．本論文は，これらの問題点を回避できる新しい低演算量かつ高解像度のレーダー信号処理アルゴリズムについて検討し，2 次元信号復元 CS アルゴリズムの構築やロバスト評価関数の導入，段階的な探索法の確立などの基礎結果を与えた上，目標の距離と速度および反射電波の到来方向(DOA)の効率的かつ高精度な推定ができる新しいアルゴリズムを提案し，その成果をまとめたものであり，全編 8 章からなる．

第 1 章の序論に続き，第 2 章は，ドップラーレーダーの基本原理と数学モデルおよびその信号処理に関する従来の結果について述べている．第 3，4 章は，時間サンプリングによる目標の距離と速度の推定は本質的に 2 次元の問題であることに着目し，2 次元 CS 復号アルゴリズムを提案すると共に，1 次元問題に変更せずに直接適用できる低演算量の技法を確立した．そして，ロバスト評価関数を導入することで非ガウスノイズ環境でも高精度推定ができるアルゴリズムを提案した．第 5 章は，MIMO レーダーの基本原理や既知結果などを述べている．第 6，7 章は，空間サンプリングによる DOA 推定問題に対し，全探索領域を細かいグリッドに分割する従来の方法と異なって，まず適切な粗さのグリッドで目標が存在する可能性のあるエリアを特定し，そして候補エリアをさらに細かく分割して高解像度で目標を検出する 2 段階探索法を提案した．また，ジョイントスパース性を考慮した上，逆行列演算が不要な適応型 DOA 推定アルゴリズムを提案し，数値例で大幅な演算量の低減と精度の向上が達成できることを示した．第 8 章は結論である．

以上, 本論文の成果は次世代 MIMO レーダーの信号処理における基本課題に対し新しい知見と解法を与えるものであり，レーダー工学と情報処理工学の発展に寄与するところが少なくない．

よって，本論文は博士（工学）の学位論文として合格と認める．